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A NEW FLEXIBLE GLOBAL POSITIONING SYSTEM (GPS) CONSTELLATION SUSTAINMENT STRATEGY

by

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14. ABSTRACT

The Global Positioning System (GPS) is now a global utility. The United States Air Force is the steward responsible for sustaining and modernizing the constellation. The current launch-to-sustain strategy implemented by the Air Force is not flexible, does not effectively support GPS modernization, and it does not lend itself to a future responsive launch paradigm. A more flexible sustainment strategy is required where the constellation is minimally sustained in preparation for a transformational modernization. A minimalist sustainment or launch-on-failure strategy has the advantage of requiring fewer total spacecraft and providing more concrete and intentional launch decisions. Once a new spacecraft block has been developed and delivered, a launch-to-transform strategy could be invoked where satellites would be launched at the maximum rate possible. This flexible launch strategy would both sustain the constellation and provide an opportunity to transform the constellation relatively quickly. It is therefore the suggestion of this paper that the current launch-on-predicted-failure strategy be replaced by the more flexible launch-on-failure strategy with the option to pursue a launch-to-transform strategy when GPS III satellites become available.

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Abstract

The Global Positioning System (GPS) is now a global utility. The United States Air Force is the steward responsible for sustaining and modernizing the constellation. The current launch-to-sustain strategy implemented by the Air Force is not flexible, does not effectively support GPS modernization, and it does not lend itself to a future responsive launch paradigm. A more flexible sustainment strategy is required where the constellation is minimally sustained in preparation for a transformational modernization. A minimalist sustainment or launch-on-failure strategy has the advantage of requiring fewer total spacecraft and providing more concrete and intentional launch decisions. Once a new spacecraft block has been developed and delivered, a launch-to-transform strategy could be invoked where satellites would be launched at the maximum rate possible. This flexible launch strategy would both sustain the constellation and provide an opportunity to transform the constellation relatively quickly. It is therefore the suggestion of this paper that the current launch-on-predicted-failure strategy be replaced by the more flexible launch-on-failure strategy with the option to pursue a launch-to-transform strategy when GPS III satellites become available.

Part 1

Background

With this milestone, GPS transitions from a revolutionary navigation aid to the world's next utility.

—Col Larry Graviss, USAF System Program Director
Navstar GPS Joint Program Office

The Global Positioning System (GPS) is now a global utility. It is used worldwide for many diverse civil and military purposes from precision farming to precision bombing. The United States Government designated the U.S. Air Force as the steward of GPS and in that role the USAF is responsible for sustaining and modernizing the constellation. This chapter provides a short description of GPS, describes what Air Force doctrine says about various strategies for sustaining satellite constellations, details the current GPS constellation sustainment strategy, and lists the objectives of this paper.

Description of GPS

GPS is a space based navigation system comprised of space, user, and control segments.

Space Segment

The space segment is a constellation of Medium Earth Orbit (MEO) satellites orbiting 20,148 km (10,872 nm) above the Earth's surface. The satellites are placed in predetermined "slots" in six orbital planes with between four and five satellites in each plane. The GPS orbits

are at an inclination of approximately 55°. Each GPS satellite orbits the entire Earth in approximately 12 hours transmitting a highly precise radio signal. All current GPS satellites carry four atomic clocks (one active, three spares) to aid in the precision of the transmitted signals.

User Segment

User (the user segment) receivers collect the signals transmitted by the satellites and calculate the time it takes the signal to travel from the satellite to the receiver. The receiver then uses the signal time travel to calculate an estimated range from the satellite to the receiver. Since the clock on the receiver cannot be accurately aligned with the atomic clock on the satellite, the receiver needs signals from four satellites to determine the position and time of the receiver.

Control Segment

The control segment monitors the health and status of each orbiting satellite, predicts the future position of the satellites and their clock drift and uploads this and other information to the satellites up to several times each day. The control segment also monitors the predicted availability of satellites around the world to ensure adequate Earth coverage. If future lapses in coverage are predicted due to perturbations to satellite orbits, the control segment tweaks the orbits to provide better coverage. If a satellite is determined to be nearing the end of its operational life, the control segment may reposition several satellites, moving a satellite with more redundancy to a more important location and moving a weak satellite to a less important location in case it fails. When satellites do fail, personnel from the 2nd Space Operations Squadron (2SOPS), who are part of the control segment, participate in the recommendation to launch a replacement satellite. Currently Air Force Doctrine Document (AFDD) 2-2 contains doctrine governing the strategies by which the Air Force decides to dispose of and launch

satellites to sustain constellations. A short summary of the applicable portions of AFDD 2-2 follows.

Sustainment Strategy Doctrine

AFDD 2-2 describes three legacy satellite constellation sustainment strategies and a fourth emerging strategy.

Launch to Deploy

The first strategy described in AFDD 2-2 is "launch to deploy." Launch to deploy is the strategy of choice prior to the Initial Operational Capability (IOC) of a constellation. IOC is defined in joint doctrine as the first attainment of the capability to employ a system effectively that is manned or operated by an adequately trained, equipped and supported military unit or force[1]. The launch to deploy strategy is used to achieve IOC through launching on a schedule planned years in advance. The schedule is determined by the availability of the satellites, boosters and launch range assets.

Launch-to-sustain

The launch-to-sustain strategy is used to replace satellites nearing the end of their useful life, replace satellites that are predicted to fail or to replace satellites that have failed in order to sustain a constellation to some desired capability. Satellites nearing the end of their useful life might still be operational but meet a particular program's disposal criteria. Disposal criteria contain aspects such as:

a. Non-recoverable bus or payload anomaly that renders it non-mission capable.
b. On-board fuel weight drops to within certain amount needed for disposal.
c. Electrical power generated by the solar arrays falls within certain number of watts of the amount of power required to dispose of the vehicle.
d. The satellite drops to one working battery.
e. The vehicle loses redundancy in a component required for disposal and the backup component starts displaying signs of impending failure.

f. If the on-board fuel weight of a satellite which is still mission capable meets criteria b, the disposal recommendation forwarded to COMSPACEAF shall include assessment of the satellite contribution to the overall GPS mission and a prediction of the ultimate achievable disposal orbit altitude.
g. Satellite requires excessive operations support to sustain.[2]

Typically launch-to-sustain launches are scheduled in advance based on predictions of when satellites will fail. More details concerning the process of how GPS satellite launches are scheduled are provided later in this chapter. If a satellite fails without a replacement launch scheduled in the near-term, several factors govern the decision of when to launch. The first factor is whether or not there is a replacement satellite available. In the case of GPS, there are 12 Block IIR satellites built and ready for launch (of the 21 built, 8 have been successfully launched, one was destroyed during a launch anomaly). However, some constellations might not have satellites immediately available. A factor related to satellite availability is booster and launch opportunity availability. Some satellite programs compete for availability of boosters and launch opportunities so it may be challenging to responsively schedule a launch. A second factor is the ability of the constellation to meet operational requirements. If the constellation can still meet operational requirements without a near-term launch, then perhaps the next scheduled launch will suffice. A third factor is range availability. GPS currently uses the Delta II rocket and since the Delta II is phasing out, reserving a launch pad is not typically an issue. Scheduling other range assets can be challenging though. A final factor that contributes to a satellite programs ability to schedule a launch if there is an unexpected failure or disposal need is the launch “call-up” time of the program. GPS advertises a 60-day launch call-up, meaning the Air Force can launch a new satellite within 60 days of notification of the requirement to launch. However, there can also be a 30-60 day on-orbit checkout period. Launching to sustain is very complicated as there are a variety of requirements and factors that need to be considered when purchasing satellites and boosters and scheduling launches.

Launch-to-Augment

The launch-to-augment strategy is much simpler than launch-to-sustain. The decision to augment a constellation is made to increase an operational capability beyond original requirements. The decision to move to a launch-to-augment strategy would be in response to a war, crisis, contingency or a perceived or real threat. GPS has not explicitly experienced a launch-to-augment strategy change but the operational requirements for GPS have experienced significant upward "creep." The original requirement was for 21 operational satellites, but in the mid 1990's Secretary Widnal directed the Air Force to increase the size of the constellation to 24 operational satellites.[3]

Launch to Operate

Launch to operate is an emerging strategy to increase the useful life of space assets. Increasing useful life would be accomplished through scheduled or responsive launches to provide on-orbit servicing such as refueling, upgrading components or repairing broken components. The launch to operate strategy is emerging because there is no current capability to service on-orbit assets in orbits other than low earth. Additionally, Low Earth Orbit (LEO) satellite servicing is reserved for a very limited number of satellites since the only method for servicing is manned space flight using the space shuttle. The launch to operate strategy is also not currently feasible because the U.S. currently does not have a responsive launch capability.

Current GPS Sustainment Strategy

As mentioned previously, the GPS constellation is currently sustained with the launch-to-sustain strategy. However, since there are many ways the launch-to-sustain strategy can be implemented, this section describes in detail how GPS launches are programmed, scheduled and how Air Force Space Command makes sustainment decisions.

The specific launch-to-sustain strategy that GPS uses could be called “launch-on-predicted-failure.” Figure 1 shows a rough diagram of how the constellation sustainment process works. Air Force Space Command Instruction (AFSPCI) 10-1213 specifies the spacelift launch strategies for Air Force programs and details the procedures followed by the Air Force for scheduling launches.[4] The process is focused on ensuring the constellation meets each programs Desired Operational Capabilities (DOC).

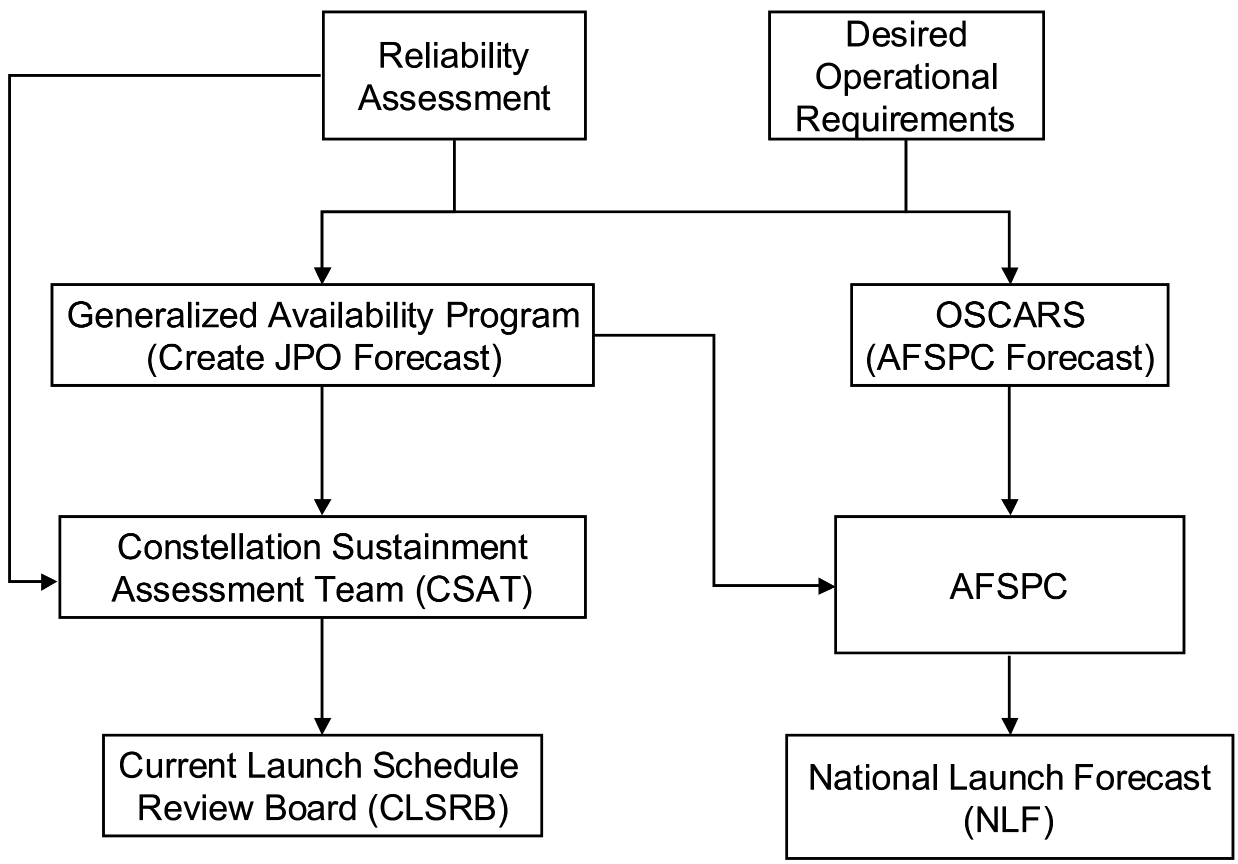


Figure 1. GPS Launch Sustainment Process

Desired Operational Capability

The DOC of GPS is directly related to the requirements outlined in the GPS Operational Requirements Document (ORD). The accuracy requirements listed in the GPS ORD have the most impact on users. However, in terms of constellation sustainment, the accuracy requirement

is not usually considered in the DOCs that determine when launches will be scheduled. The only time accuracy is considered is if a satellite's performance is degrading to the point where it no longer meets accuracy requirements. In nearly all other circumstances satellite geometry is the overriding concern. Since GPS accuracy is a function of satellite geometry through Dilution Of Precision (DOP), GPS DOCs are anchored on the availability of a certain number of satellites in certain orbital locations. DOP is a user/satellite geometry parameter that represents the contribution of the geometry of the satellites to overall position error. Additional details on how the geometry of the constellation impacts accuracy can be found in other GPS references.[5,6]

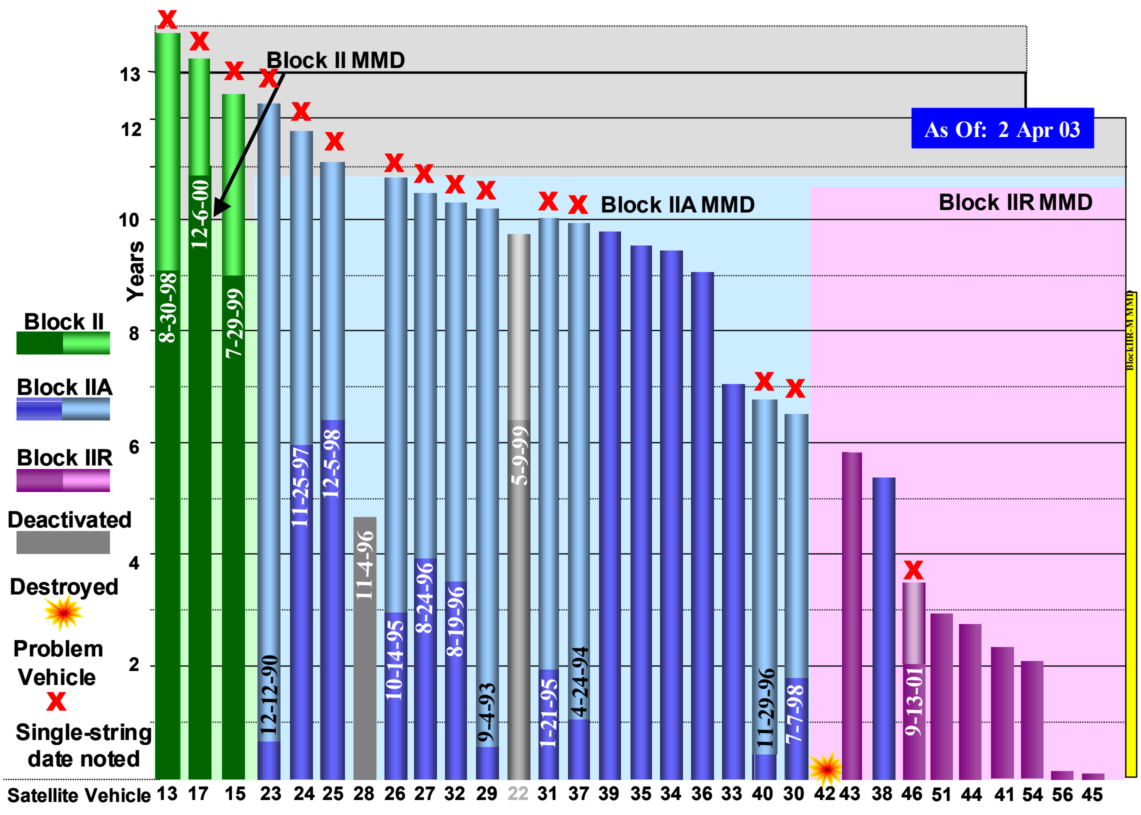


Figure 2. Satellite Age and Block Mean Mission Duration[7]

As mentioned earlier in this paper, the original requirement for the number of GPS satellites on orbit was 21. The specified requirement was 98% availability of 21 satellites. However, due to growing military and civil reliance on GPS and the fact that GPS is an important part of our

critical national infrastructure[8], the requirement was increased to 24 satellites on orbit. The Air Force in-turn modified the 98% availability of 21 satellite requirement to 95% availability of 24 satellites. However, having 24 satellites on orbit does not guarantee the Earth coverage those satellites provide will be optimal, nor that those 24 satellites will be available 95% of the time. Therefore, to meet the requirement of 95% availability of 24 satellites, 26 to 28 satellites are typically on orbit. As Figure 2 shows, there are currently 28 satellites on orbit. With all that said, the GPS DOC sought by Air Force Space Command is 95% availability of 24 satellites.

Constellation Sustainment Process

Ensuring 95% availability of 24 GPS satellites, in the long term, is a challenging task. The sustainment process starts each year with the update of each satellite's reliability parameters, also known as the reliability assessment. The reliability assessment is performed twice a year by the Aerospace Corporation and approved by the GPS Joint Program Office (JPO) in Los Angeles, California. The reliability assessment is also forwarded to the AFSPC/DO for review and concurrence. Aerospace performs two types of reliability assessments, one on satellites that are on orbit and one for satellites not yet flown. Reliability parameters such as Mean Mission Duration (MMD) and failure rate alphas and betas[9] are calculated for each block of satellites (IIA, IIR, IIR-M, IIF and III). The MMDs and current satellite ages are summarized in Figure 2. The alphas and betas for the block IIA and IIR satellites that are on orbit are calculated specifically for each individual satellite. The predicted life of the satellites is reduced, on an individual basis, based on how long the satellite has been on orbit and if some of its redundant systems have failed. The reliability assessment for the satellites not yet flown is updated based on design changes, trend analysis and component random failure rates. The MMDs of new satellite blocks change very rarely. The MMDs of satellite blocks currently being flown, but for

satellites not yet launched, change typically less than 0.25 years, mostly based on observed performance.[10]

Once the reliability parameters are updated they are input into two satellite failure prediction models. Aerospace uses the Generalized Availability Program (GAP) and AFSPC/DR uses Operational Satellite Constellation Availability and Reliability Simulations (OSCARS). Both software suites perform Monte Carlo simulations to predict the size of the constellation based on random and probability based satellite failures. Launch dates are input into GAP and OSCARS at appropriate times to attempt to keep the availability of 24 satellites above 95%. Figure 3 shows a sample GAP output and the assumptions used in the run.

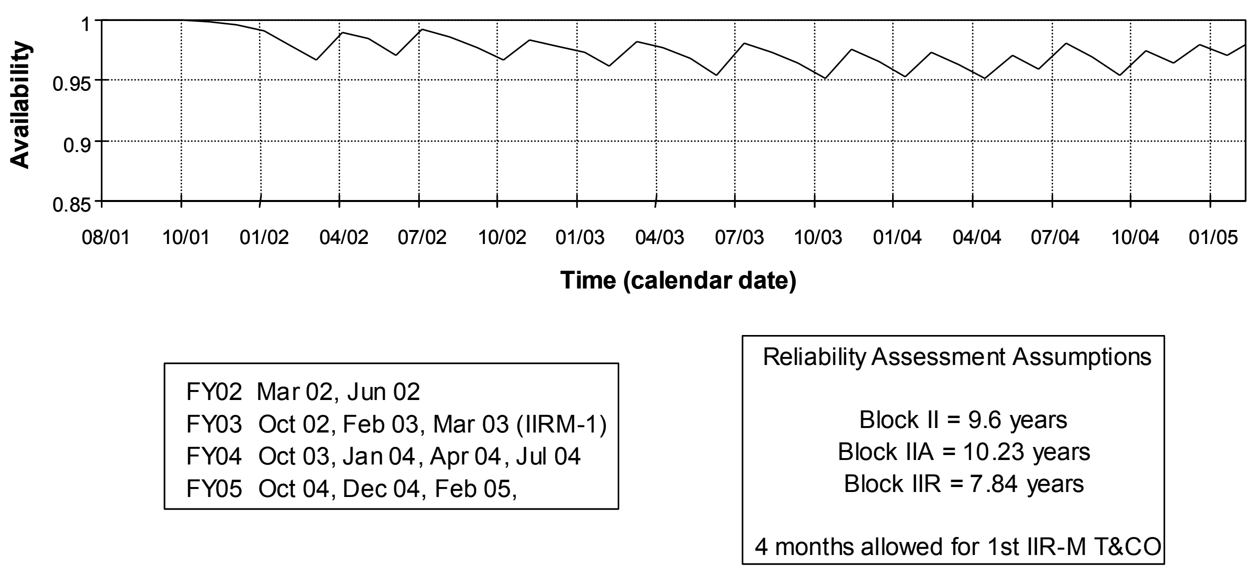


Figure 3. Sample GAP Output[11]

The outputs from GAP and OSCARS are compared with each other and after their differences are reconciled, the launch dates that best meet the DOC are formalized as input for the Current Launch Schedule (CLS) and the National Launch Forecast (NLF). The CLS is an executable 18-month launch forecast while the NLF may contain over 10 years of predicted

launches. The CLS is part of a three year forecast called the Space Launch Manifest (SLM) and is used for one or two year programming while the NLF is used for the AFSPACE Program Objective Memorandum (POM) and Future Year Defense Budget (FYDP).

The initial vetting of the CLS occurs at Constellation Sustainment Assessment Team (CSAT) meetings that take place twice a year or approximately 90 days before scheduled launches. At the CSAT the GPS JPO, 2SOPS and many other agencies brief their view as to whether or not a scheduled launch is needed or if there should be any changes to the CLS. The 14th AF consolidates the CSAT input and makes launch and CLS recommendations to the Commander of AF Space Command (COMAFSPACE). COMAFSPACE approves or disapproves the launch recommendation, but the CLS is approved at a CLS Review Board (CLSRB) held twice annually.

The most pertinent part of the sustainment decision to this paper is the basis for the launch recommendation that comes from the CSAT. As stated earlier, the decision is based on the predicted failure of satellites. If the reliability data presented by the GPS JPO and the operational experience of 2SOPS coincide to indicate an imminent failure, then the decision is easy. However, if the recommendations from 2SOPS and the JPO are not the same, then the 14th AF has to resolve the issues and make a recommendation to COMAFSPACE. There are several factors that influence the launch decision: the launch schedule, the overall health of the constellation, the impact of predicted satellite failures, the strength of the plane in which the satellite in question resides, any programmatic schedule issues, and the real-world situation. Once the launch decision recommendation is forwarded to COMAFSPACE, the entire process starts again with another Aerospace Corporation satellite reliability assessment.

Objectives

The constellation sustainment strategy for GPS is very challenging. There are many competing factors that potentially drive launch decisions that might not be warranted. Launching a satellite based on a failure prediction can cause problems. First, the wrong plane might be chosen; a weak satellite in a different plane may fail before the satellite that is predicted to fail. Additionally, a satellite that is predicted to fail could live one to two years past when it is predicted to fail. Finally, a satellite may fail unexpectedly and if there is no scheduled launch in the short term it may be challenging to launch a replacement, as the current launch decision process is not very responsive. Therefore, the objective of this paper is to present a more appropriate launch decision criteria that superbly stewards GPS as a global utility, improves employment flexibility, enables transformation acceleration, and empowers a responsive launch paradigm.

Superbly Steward GPS as a Global Utility

The first goal of a new GPS sustainment strategy is to superbly steward GPS as a global utility. GPS has millions of users worldwide and the number of new users is nearly doubling every year.[12] A civil and military chaired oversight council called the Interagency GPS Executive Board (IGEB) oversees GPS. However, the DoD does the programming, planning and budgeting for GPS along with all of its other space programs, even though both military and civilian users rely on it. Unfortunately, budgets are limited and the GPS budget is limited along with the rest of DoD. Therefore, a new launch strategy should attempt to superbly steward the constellation by optimizing coverage while minimizing the number of satellites on orbit.

Improves Employment Flexibility

A new launch strategy should also improve employment flexibility in terms of the geometry of the constellation. Recent studies have shown that a three-plane constellation at slightly higher altitude could be both easier to sustain and could provide better Earth coverage.[13] A three-plane constellation is easier to sustain because two satellites could be launched with one booster. Better Earth coverage might be possible in three planes with a 27-33 satellite constellation while a six planes provides better coverage with a 24 constellation satellite.[14] It would be very challenging and would potentially require additional satellites to retrench the constellation to three planes from the current six-plane constellation. Therefore, a new sustainment strategy should be flexible enough to support a drastic change in constellation geometry.

Enable Transformation Acceleration

A third objective in seeking a new launch strategy is to enable the acceleration of GPS transformation. Much has been published about the modernization of GPS through the addition of a new military signal and a second civil signal to as many as 12 block IIR satellites and the further addition of a third civil signal to the block IIF satellites.[15] A transformational GPS upgrade is also being studied as part of GPS III. The current launch schedules and funding profiles show GPS III achieving Initial Operating Capability (IOC) in the 2016-2019 timeframe. One reason why IOC is so late is because of the current sustainment strategy. Therefore, a new strategy should accommodate and enable an acceleration of the reaching of IOC of GPS III.

Empower a Responsive Launch Paradigm

Finally, a new GPS launch sustainment strategy should empower a responsive launch paradigm. The Air Force continues to seek the ability to provide responsive launch.[16] Responsive launch is the ability to launch a satellite in days or weeks instead of multiple months.

Unfortunately, with the complexities and significant costs associated with space launch it may be decades before a responsive launch capability is realized. Therefore, a new GPS sustainment strategy should be able to take advantage of responsive launch without being reliant on it.

Background Summary

GPS is now a global utility used by millions in the U.S. and abroad. The Air Force sustains GPS with a launch-on-predicted-failure sustainment strategy that can potentially place more satellites in orbit than is required to meet the current desired operational requirement of 95% availability of 24 satellites. A new more flexible launch strategy is next proposed that better stewards the constellation, improves employment flexibility, enables the acceleration of transformation and empowers a responsive launch paradigm. The first step is to move to a launch-on-failure strategy.

Notes

[1] Joint Publication (JP) 1-02, *Department of Defense Dictionary of Military and Associated Terms*, 14 August 2002, 215

[2] GPS Sustainment Concept of Operations (CONOPS), 28 December 2001, 3-16

[3] Borchelt, Rick, "*President Opens Door to Commercial GPS Markets*," The White House, Office of the Press Secretary, 29 March 1996, n.p..

[4] Air Force Space Command Instruction (AFSPCI) 10-1213, *Spacelift Launch Strategy and Scheduling Procedures*, 1 July 1998, 2.

[5] Kaplan, Elliot D, *Understanding GPS: Principles and Applications*, (Boston: Artech House, 1996), 261-269.

[6] Hofman-Wellenhof, B. et.al, *Global Positioning System: Theory and Practice*, (New York: Springer, 2001), 271-275.

[7] 2nd Space Operations Squadron Weekly Satellite Status Briefing, 2 April 2003.

[8] Bremer, Paul L. III and Meese, Edwin III, "*Defending the American Homeland*" A Report of The Heritage Foundation Homeland Security Task Force. Washington D.C. 2002.

[9] Lawless, Jerald F., *Statistical Models and Methods for Lifetime Data*, (Wiley-Interscience, 2002).

[10] The 0.25 year number is based on my anecdotal observations while at the GPS JPO.

[11] Goldstein, David B., "*Constellation Re-optimization (27+0) for the GPS Executive Council*," Briefing, Colorado Springs, Colorado, 19 January 2001.

Notes

[12] *Global Positioning System Market Projections and Trends in the Newest Global Information Utility*, The International Trade Association, Office of Telecommunications, U.S. Department of Commerce, September 1998.

[13] Kelly, Clifford W., *Orbital Optimization of the GPS Constellation and Its Effect on Accuracy and Availability*, Proceedings, Institute of Navigation, GPS National Technical Meeting, 1997.

[14] Ibid.

[15] Loverro, Douglas, *GPS Modernization*, Plenary Session Institute of Navigation 58th Annual Meeting, Albuquerque, NM, 24 June 2002.

[16] Scott, William B., *Rapid Response*, Aviation Week and Space Technology, 7 April 2003.

Part 2

Launch-on-Failure (27+0)

The enemies of change are often those who would benefit most from it.

—Anonymous

There are advantages and disadvantages of every launch sustainment strategy. This chapter describes the strengths and limitations of both the launch-on-predicted-failure and launch-on-failure paradigms. To implement a launch-on-failure strategy the constellation geometry should be changed from an optimized 24 satellite constellation with X spares (24+X) to an optimized 27 satellite constellation with no spares (27+0). This chapter also describes how the GPS constellation would be modified to support a launch-on-failure sustainment strategy, i.e., moving to an optimized 27+0 configuration.

24+X Constellation

The 24+X constellation places 24 satellites in "prime" locations. These 24 prime and X spare locations are identified in Interface Control Document (ICD)-GPS-200C.[1] In the 24+X constellation, the 24 satellite locations are optimized to provide the best coverage those 24 satellites can attain. The X spares do contribute to global coverage but the coverage of a constellation where all 27 satellites are in optimized locations provides better coverage, as will be seen later in this chapter.

Launch-on-Predicted-Failure Strengths

The launch-on-predicted-failure strategy has served GPS sustainment well since its IOC in 1995. This long-lived strategy has several strengths. First, the processes used by the operators and acquirers are rigorous, full of engineering discipline and appropriate. All satellite disposal and launch decisions are carefully thought out, rigorously analyzed by multiple agencies and the processes outlined in AFSPCI 10-1213 are fittingly applied. The launch-on-predicted-failure strategy is also flexible in terms of constellation size and programming and budgeting. The constellation may grow to as many as 29 satellites or may only have 26. Additionally, since failures are predicted, launches can be scheduled based on failure predictions and funds can be programmed to support scheduled launches.

The launch-on-predicted-failure strategy has also been very effective in surpassing the DOC for GPS. Since the decision to maintain 24 satellites on orbit, the Air Force has achieved nearly 100% availability of 24 satellites when the requirement is only 95%. Launch-on-predicted-failure also negates the need for definitive and aggressive disposal criteria. Weak satellites are kept "alive" as long as possible and are rarely preemptively disposed. The final strength of launching on predicted failure is it is an approved strategy that is currently being implemented on several Air Force programs. Therefore, there is no institutional inertia to overcome to attempt to move to a different strategy.

Launch-on-Predicted-Failure Limitations

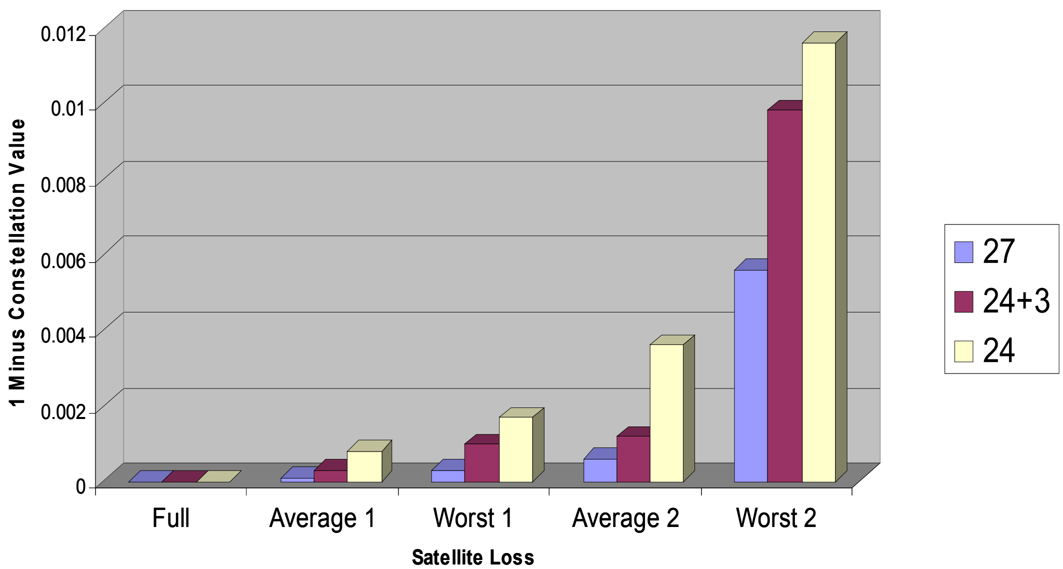
While the predicted failure strategy has strengths, it also has several significant limitations. First, it does not provide definitive and precise launch criteria. The process for predicting launch failures is rigorous, but it is still based on probabilities and engineering judgment. No statistics have been kept to show the accuracy of predictions and there is often just as high a probability

that the wrong plane will be chosen as the right plane. Additionally, the process is overly cautious, as indicated by the achievement of nearly 100% availability of 24 satellites. The launch-on-predicted-failure strategy also does not provide criteria by which the constellation is optimized, nor does it fully utilize all the satellites on orbit. As an example, an optimized 27 satellite constellation might have better coverage than a non-optimized 29 satellite constellation. Finally, the launch-on-predicted-failure strategy is a challenge to the acquisition community. By overshooting the requirement for 95% availability of 24 satellites there is some risk satellite availability could be jeopardized in the future. Also, if unexpected failures occur or if predicted failures do not occur, it can strain the inherently inflexible launch programming and budgeting system.

Launch-on-Failure Strengths

Several of the launch-on-predicted-failure limitations are mitigated by the launch-on-failure strategy. First, launch-on-failure provides definitive launch decision criteria. Launches are scheduled only when they are needed and the correct plane and slot are always chosen. Launch-on-failure also optimizes GPS system resources. As Figure 4 shows, the constellation has better coverage and is thus more robust if unexpected failures occur when the 27+0 optimization is simulated versus the 24+3 constellation[2]. Furthermore, as Figure 5 shows, the launch-on-failure strategy (shown as launch on need in the figure) provides better predicted availability in the long-term than the launch-on-predicted-failure strategy.[3] Unfortunately, it is difficult to quantify the savings in satellite years of moving to a launch-on-failure strategy. However, a launch-on-failure strategy will always launch at a slower rate than a launch-on-predicted-failure strategy. Launch-on-failure will save as many satellite years as satellites live longer than predicted.

Launch-on-failure also contributes to optimizing system resources by making satellite maintenance scheduling easier due to improved constellation robustness and because there will be fewer satellites on orbit in the long term. Two additional strengths of the launch-on-failure strategy are that it could distinctly take advantage of a future responsive launch capability[4] and, as will be shown later in this chapter, it is not operationally challenging to move to the 27+0 configuration.



0.0001 = 2 x area of Alaska for 21 minutes

Figure 4. Constellation Value Satellite Loss Comparison[5]

Launch-on-Failure Limitations

Launch-on-failure is also not without limitations. There is the potential for capabilities creep where users become accustomed to the improved coverage of a 27 satellite constellation and so the new DOC changes to 95% availability of 27. There is also less margin for error in predicting satellite failures. The constellation becomes more robust but it becomes more dependent on older, less reliable satellites. Additionally, the constellation will not achieve 100%

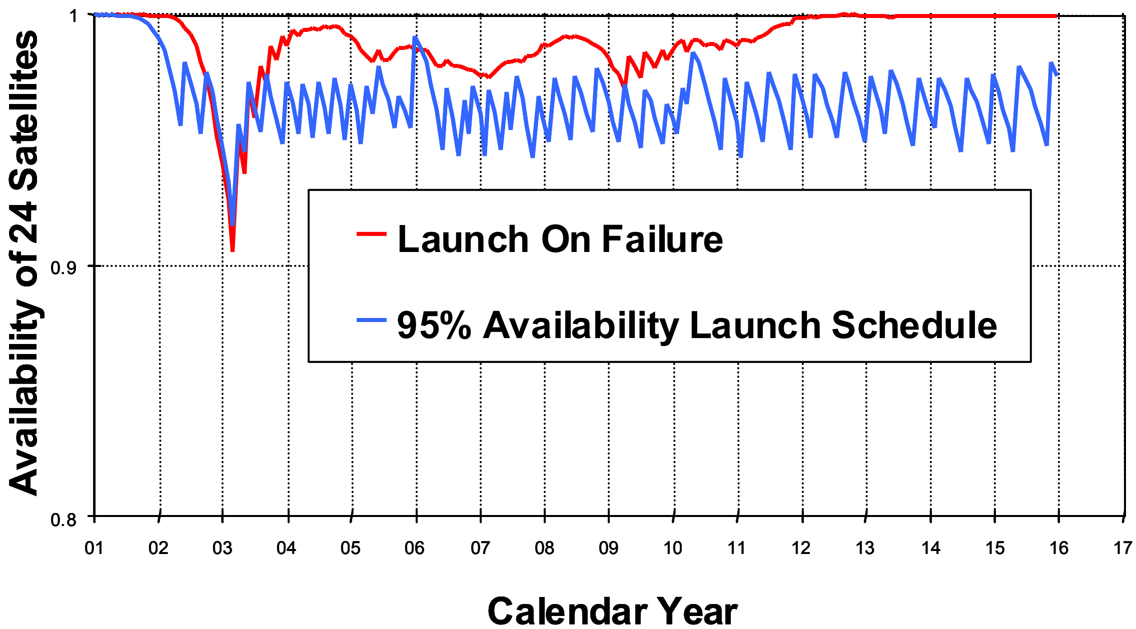


Figure 5. Launch On Failure vs. Launch on Schedule[6]

availability of 24 satellites as has been experienced with the launch-on-predicted-failure strategy. Also, as global coverage expectations grow, it may be politically difficult to scale back to the "real" requirement of 95% availability. Finally, the new paradigm will be a challenge to the Planning, Programming and Budgeting System (PPBS). Flexibility will need to be added to the PPBS since the number of launches per year will not be easily or accurately predicted. Transforming the PPBS is the most challenging aspect of moving to a true launch-on-failure paradigm.

How to Get There From Here

The transition to an optimized 27+0 constellation is not overly complex, nor does it require the launch of additional satellites. Symmetry in the constellation provides a logical location for the additional 3 satellites. Figure 6 shows the constellation in a 24+4 configuration--an optimized 24 satellite constellation with 4 spares. The optimized 27 satellite constellation is shown in Figure 7. Here three new "close pairs" in alternating planes are created and three

current "prime" slots and their close pairs would move 8.5 degrees in mean anomaly. Prime slots are the optimized slots. The current spares in the B, D and F planes could support near term repositioning into the new configuration. Another alternative would be to reposition the three prime slots and replace the three satellites in the current spare slots with three new satellites in close pairs. However, the easier and more pragmatic approach is to reposition the pairs to their new orbital positions as shown in Figure 7.

Launch-on-Failure Summary

This chapter focused on the strengths and limitations of the current launch-on-predicted-failure sustainment strategy and a new launch-on-failure strategy. The current paradigm provides nebulous launch criteria, challenges the GPS acquisition strategy and does not take full advantage of every satellite on orbit by optimizing its coverage. It does however, have established rigorous processes, which, while cautious, have sustained the constellation beyond the DOC of 95% availability of 24 satellites for many years.

The 27+0 re-optimization or launch-on-failure strategy addresses the limitations of the launch-on-predicted-failure strategy. First, it provides a more definitive launch decision process and while it will require changes to the PPBS, it better stewards the constellation and provides better worldwide coverage when expected or unexpected satellite failures occur. However, with the launch-on-failure strategy it will be difficult and time consuming to transform the constellation with the block III satellites. Therefore, a flexible strategy is needed to launch-to-transform.

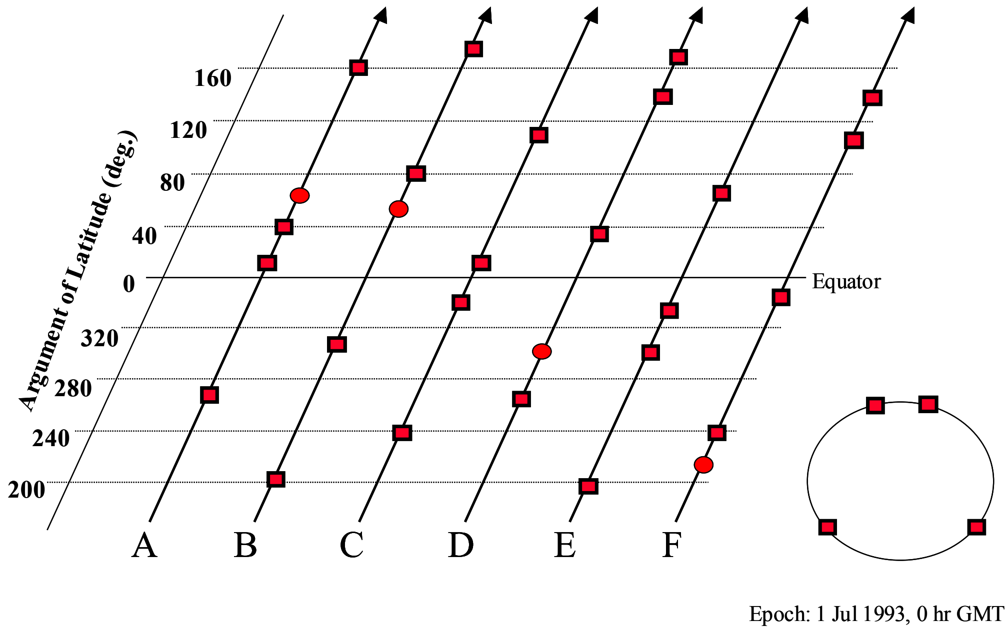


Figure 6. GPS Constellation With 24 Optimized Slots and Four "Spares"[7]

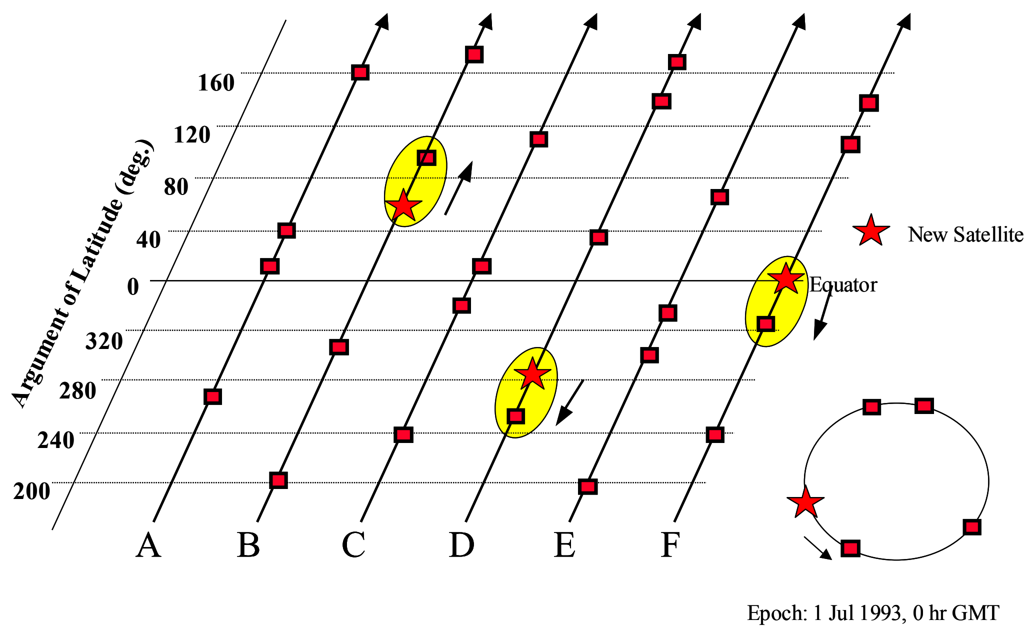


Figure 7. GPS Constellation With 27 Optimized Slots[8]

Notes

[1] Interface Control Document (ICD)-GPS-200C, Navstar GPS Joint Program Office, 12 April 2000.

[2] Constellation value is a quantity that describes the contribution of a satellite to Earth coverage. As Figure 4 indicates, a constellation value of 0.0001 is 21 minutes of time over roughly the area of twice the size of Alaska or 1,000,000 square miles. The 21 minutes are not necessarily sequential and the area is not necessarily adjacent. As a point of reference, the coverage requirement from the GPS ORD is PDOP $\leq$ 6 0.98 of time and area over a day. However, losing the two most important satellites to coverage yields 0.9944, still significantly over the coverage requirement. "Worst 2" refers to the two most important satellites in terms of their contribution to coverage. "Average 2" refers to two average satellites in terms of their contribution to coverage.

[3] Figure 5 shows a comparison of the probability of having 24 satellites on orbit using a launch-on-predicted-failure strategy versus a launch on need or launch-on-failure strategy. The scheduling of launches for the blue line (launch-on-predicted-failure) occurs when a satellite is available from the manufacturer and the probability of having 24 satellites on orbit drops below 95%. The scheduling of launches for the red line (launch on need or launch-on-failure) occurs only when the number of satellites in the constellation drops below 27. It is interesting to note that there is better predicted availability using the launch-on-failure strategy than using the launch-on-predicted-failure strategy. This can occur using fewer satellites because if 27 satellites are on orbit but their statistics indicate imminent failure, the probability of having 24 satellites might be below 95%.

[4] Scott, William B., *Rapid Response*, Aviation Week and Space Technology, 7 April 2003.

[5] Goldstein, David B., *Constellation Re-optimization (27+0) for the GPS Executive Council, Briefing*, Colorado Springs, Colorado, 19 January 2001.

[6] Ibid.

[7] Ibid.

[8] Ibid.

Part 3

Launch-to-Transform

Flexibility is the key to airpower.

—Anonymous

Launch-to-transform is a strategy where satellites would be delivered and launched at the maximum rate possible to quickly provide a revolutionary new capability. The Air Force should develop a launch-to-transform strategy to mitigate the potential for future threats to the GPS and other Air Force satellite constellations. This chapter describes limitations to current doctrine, identifies why a launch-to-transform strategy is needed and discusses several additional considerations.

Limitations of Current Doctrine

Current doctrine does not provide launch strategies that address modernization or transformation. The four launch strategies are launch to deploy, launch-to-sustain, launch-to-augment and launch to operate[1]. The Air Force is researching how spiral development[2] can be utilized to deliver incremental improvements to satellite and weapon systems. If spiral development is implemented or if revolutionary new capabilities (modernization or transformation) are infused into current satellite systems, current doctrine does not address how these improvements should be employed. Modernization or transformation should be implemented differently than the current launch strategies.

Why Develop a Launch-to-Transform Strategy

It is likely projected threats to GPS will not materialize prior to the planned IOC of GPS III in the FY16 to FY19 timeframe. However, if the threat analysis indicates the transformational capabilities of GPS III are required prior to the planned IOC, then it would be prudent to have a launch-to-transform strategy articulated and achievable. The launch-to-transform strategy needs to be articulated in doctrine and needs to be achievable in terms of having processes and systems in place that can take advantage of it.

Another reason to articulate and plan for a launch-to-transform strategy is the potential for counter-space threats from other nations. In the next ten years adversaries may seek asymmetrical means of countering U.S. space dominance. One way to deter such action is for the U.S. to develop a responsive launch capability, articulate concepts of operation whereby responsive launch could be utilized, and plan for systems that can take advantage of responsive launch. GPS is certainly a system that could utilize responsive launch-to-transform or repopulate the constellation.

A final reason to pursue the launch-to-transform strategy is that articulating it in doctrine provides support for planning and budgeting to support such a strategy in the future. When the strategy is articulated the acquisition system can begin to develop and field systems in such a way as to take advantage of it.

Other Considerations

There are several additional GPS considerations that need to be addressed in the development of a launch-to-transform strategy. The first consideration is limitations on the size of the constellation. The number of satellite Pseudo Random Noise (PRN) codes is one of several issues that currently limit the size of the GPS constellation. 32 PRN codes are identified

in ICD-GPS-200C.[3] 30 of the 32 PRNs are available for satellites and there are user equipment issues with PRN 0. Therefore, the current constellation is limited to a maximum of 29 operational satellites. If a launch-to-transform strategy were to be developed and implemented on GPS, the next block of satellites, the next generation of user equipment and the control segment would all need to be modified if the launch-to-transform strategy includes the need to increase the size of the constellation above 29, which it most likely will.

A second consideration that needs to be addressed prior to the development of a launch-to-transform strategy is the responsiveness of GPS to quickly develop and launch satellites. The current launch call-up procedures can accommodate up to six launches per year, however, the National Launch Forecast (NLF) shows between three and four launches per year for IIR and IIF satellites but only one to two launches per year for GPS III satellites[4]. The reason why only one to two GPS III satellites are projected to be launched per year is either because the GAP and OSCARS analyses project that is all that will be needed or because the contractor is projecting to only be able to deliver one to two satellites per year. If the reason is the latter, the acquisition community needs to address this limitation prior to awarding the contract. Additionally, it is important to note that Air Force planners are assuming two satellites will be launched at a time on GPS III.

A third and final consideration that needs to be addressed is the question of when and if the launch strategy should return to launch-on-failure. It may be that the effects of only a few GPS III satellites may transform the military capability of GPS. For instance, having only one GPS III satellite in view may provide the capability needed to overcome the threats in the FY12 timeframe. Therefore, launching only six satellites may be enough to transform the constellation. In this case, the launch-to-transform strategy would be to launch the six satellites

in as rapid a manner as possible, potentially in three launches over four to six months. Then once the constellation is effectively transformed, the launch strategy can return to launch-on-failure.

Launch-to-Transform Summary

Current Air Force and joint doctrine do not contain strategies whereby a satellite constellation can be rapidly modernized or transformed. The launch to deploy and launch-to-sustain strategies do not adequately address this emerging need. GPS III is a program that could and may need to rely on a strategy where a constellation is rapidly infused with transformational technology. These doctrinal and therefore planning and budgeting limitations currently plaguing GPS and other programs can potentially be addressed with the articulation of a standalone launch-to-transform strategy or a modification to the launch to deploy strategy. Either way, current doctrine needs to be updated to better address responsive launch.

Notes

[1] Air Force Doctrine Document (AFDD) 2-2, *Space Operations*, 27 November 2001.

[2] Brown, David, *Evolutionary Acquisition and Spiral Development*, Briefing, Technology and Engineering Department, Defense Acquisition University.

[3] Interface Control Document (ICD)-GPS-200C, Navstar GPS Joint Program Office, 12 April 2000.

[4] Col James S. Haywood, GPS Joint Program Office, memorandum, subject: Navstar GPS input for National Launch Forecast (NLF), 15 October 2002.

Part 4

Recommendations and Conclusion

GPS is now a highly utilized and relied upon global utility. The U.S. military relies on GPS 24/7/365.25 practically worldwide for routine missions, and at times, the lives of countless innocent civilians and U.S. and coalition soldiers, sailors, marines and airmen depend on its accurate, precise and ubiquitous signals. The superb availability and coverage GPS has delivered must be maintained in the near term and in the future. Therefore, the following recommendations are made to improve the processes and doctrine by which the GPS constellation is sustained. Following the recommendations is a short conclusion for this paper.

Recommendations

The five recommendations below address current sustainment processes and doctrine for GPS. The first three recommendations address the launch-on-failure strategy and the first two objectives of this paper; the last two address the launch-to-transform strategy and the last two objectives.

1. Reconfigure the GPS constellation to the optimized 27+0 configuration mentioned in chapter 2.
2. Seek modifications to the PPBS to better accommodate the launch-on-failure strategy.
3. Once the constellation is reconfigured and the PPBS is adequately modified, implement the launch-on-failure strategy.
4. Develop and publish a launch-to-transform strategy either as a supplement to launch to deploy or as a standalone strategy.

5. Begin the process of building into GPS III satellites, launch systems, user equipment and control segment the ability to accommodate more than 29 satellites and the ability to utilize responsive launch.

Summary

Chapter 1 of this paper describes the Global Positioning System, summarizes current Air Force sustainment strategies as outlined in AFDD 2-2, and elucidates the current GPS sustainment strategy, processes and Desired Operational Capabilities (95% availability of 24 satellites). Chapter 1 also outlines four objectives sought in addressing potential updates to the GPS sustainment strategy: 1) Superbly Steward GPS as a Global Utility, 2) Increase Deployment Flexibility, 3) Enable Accelerated Transformation, and 4) Empower Responsive Launch.

Chapter 2 presents the strengths and limitations of the launch-on-predicted-failure and launch-on-failure strategies and why we should move to the launch-on-failure strategy. The strengths and limitations are summarized in Table 1. Chapter 3 discusses the limitations in current doctrine and why a launch-to-transform strategy should be developed and articulated in doctrine.

Conclusion

The GPS constellation can be sustained in a more robust, flexible and deliberate manner if the constellation is optimized to the 27+0 configuration and the launch-on-failure strategy is adopted. Additionally, potential future threats to GPS services and satellites can be mitigated by the development and programming for a launch-to-transform strategy. Launch-on-failure and launch-to-transform can significantly contribute to the continued success of the GPS constellation. They both should be given due consideration.

Table 1. Strategy Strengths and Limitations Summary

	Limitations	Strengths
Launch-on-predicted-failure	1. Processes based on engineering judgment 2. Over cautious predictions 3. Coverage and satellite usage not optimized 4. Risks future satellite availability	1. Rigorous, disciplined processes 2. Flexible for PPBS 3. Maintained 100% availability of 24 satellites 4. Negates need for aggressive disposal criteria 5. Enjoys institutional inertia
Launch-on-failure	1. Potential for desired capability creep 2. Less margin for error in planning 3. Constellation would rely more on less redundant satellites 4. Less likely to achieve 100% availability of 24 satellites 5. Challenging to PPBS	1. Provides definitive launch criteria 2. Optimized system resources 3. Better future predicted availability 4. Guaranteed slower launch rate 5. Easier maintenance scheduling 6. Can take advantage of responsive launch 7. Not overly difficult to implement

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